#4

ORIGINAL CONTRIBUTION

Stimulating Multiple Respiratory Muscles With Intramuscular Permaloc Electrodes

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Received December 24, 2009; accepted January 4, 2010

Abstract

Objective: To test the feasibility of implanting intramuscular electrodes (Permaloc, Synapse Biomedical Inc, Oberlin OH) with self-securing polypropylene anchors to stimulate upper-intercostal and abdominal muscles plus the diaphragm.

Methods/Results: In 6 anesthetized dogs, 12 Permaloc electrodes were implanted in the 3 respiratory muscles (4 in each muscle group). Tidal volume with diaphragmatic stimulation was 310 ± 38 mL (mean ± SE); with upper intercostal stimulation, it was 68 ± 18 mL; and with combined diaphragm intercostal stimulation, it was 438 ± 78 mL. By study design, stimulation in the upper intercostal muscles was limited to not more than slight/moderate contraction of the serratus and latissimus muscles overlying the ribs. Abdominal muscle stimulation produced exhaled volumes of 38 ± 20 mL (this stimulation was limited by the maximal output of the stimulator of 25 milliamperes). Combined diaphragm intercostal stimulation followed by abdominal muscle stimulation increased exhaled volumes from 312 ± 31 mL to 486 ± 58 mL ($P = 0.024$).

Conclusions: Permaloc electrodes can be successfully implanted in upper intercostal and abdominal muscles in addition to the diaphragm. Combined diaphragm intercostal stimulation followed by abdominal muscle stimulation increased the exhaled volumes recorded with diaphragmatic stimulation alone.

J Spinal Cord Med. Apr 2010;33(2):135–143

Key Words: Spinal cord injuries; Respiratory muscles; Respiration; Phrenic pacing; Electrical stimulation, functional; Respiratory distress

INTRODUCTION

Most patients with upper cervical spinal cord injury require ventilator support (1,2). Ventilatory support is usually maintained with positive pressure ventilation and, less often, by activation of the diaphragm muscle through phrenic nerve stimulation. Phrenic nerve stimulation is achieved with electrodes placed adjacent to the phrenic nerve. These electrodes are usually implanted in the mediastinum. More recently, diaphragmatic intramuscular electrodes provided with self-securing polypropylene anchors (Peterson, Synapse Biomedical Inc, Oberlin, OH) have been used to deliver phrenic nerve stimulation (3,4). Potential limitations of phrenic nerve stimulation, whether delivered with mediastinal or intramuscular electrodes, include insufficient ventilation due to muscle atrophy, preexisting partial damage of the phrenic nerve motor neurons, and inward rib cage movement that can accompany diaphragmatic contractions. This inward movement of the diaphragm diminishes the efficacy of phrenic pacing to generate tidal breathing. To overcome these limitations, combined stimulation of upper intercostal and diaphragm muscles has been proposed (5–9). The goal of intercostal stimulation is to stabilize and expand the thorax during diaphragm stimulation.

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This investigation was based upon work supported by the Office of Research and Development, Rehabilitation Research and Development Service, of the Department of Veterans Affairs (#B3008P). Support of Synapse Biomedical Inc for providing electrodes and stimulators and technical assistance is gratefully acknowledged and was provided under a Material, Cooperative, Research and Development Agreement between the company and the Veterans Administration.

The ventilation achieved with combined stimulation of intercostal and diaphragm muscles can be further augmented with stimulation of the abdominal expiratory muscles during exhalation (5,9). Stimulation of the abdominal expiratory muscles causes active exhalation below functional residual capacity. Exhalation below functional residual capacity augments inhalation by storing elastic recoil pressure, which is released at the end of exhalation. In addition to assisting the inspiratory muscles, abdominal muscle stimulation has the potential to improve cough and thus removal of respiratory secretions, a common cause of morbidity and mortality in patients with spinal cord injuries (1).

In patients (10–18) and laboratory animals (5–7,19), stimulation of extradiaphragmatic muscles has been achieved with the use of ventral epidural electrodes implanted in the spinal foramina close to the ventral roots and with surface electrodes (expiratory muscles). However, stimulation of the ventral spinal cord is limited by the invasive surgery required to implant the electrodes. Stimulation of the abdominal muscles with surface electrodes is limited by the need for external wires and problems with daily application of skin electrodes.

Accordingly, the current investigation was designed with 2 aims: first, to develop a surgical technique to implant minimally invasive, intramuscular Permaloc electrodes (Permaloc is an alternative name for Peterson electrodes used in animal studies) provided with self-securing polypropylene anchors in the upper intercostals and abdominal wall muscles; and second, to determine whether using these electrodes to stimulate the upper intercostal muscles in synchrony with the diaphragm, followed by abdominal muscle stimulation, would augment the tidal volumes elicited by diaphragm stimulation alone.

METHODS

The local Institutional Animal Studies Committee approved these studies. Two male and 4 female adult short-haired dogs weighing 20 to 27 kg underwent 2 survival surgeries. During the first surgery, intramuscular electrodes with self-securing polypropylene anchors were placed bilaterally in the diaphragm and in the abdominal muscles. During the second surgery, 2 pairs of intramuscular electrodes were implanted bilaterally in the upper intercostal muscles.

General Anesthesia

General anesthesia was initiated with intravenous propofol (6 mg/kg bolus) followed by isoflurane (2–3%) delivered through an endotracheal tube. The dogs were maintained at a surgical plane of anesthesia. Preoperative atropine (0.05 mg/kg intramuscularly) was administered to reduce secretions. Body temperature was kept at 38°C with a heating pad. During surgery, the animals were artificially ventilated (Drager Anesthesia Ventilator, Louisville, KY). Ventilation was titrated to maintain a partial pressure of end-tidal carbon dioxide at 35 mmHg (Tidal Wave Capnograph/Oximeter, DRE Veterinary, Louisville, KY).

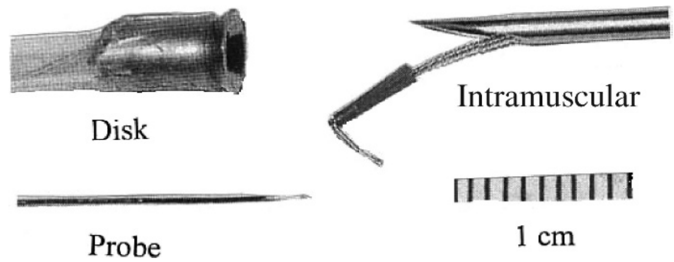

Figure 1. *Electrodes used in this study. The disk and 5-mm probe electrode are shown on the left. A Permaloc intramuscular electrode mounted in the 16-gauge insertion needle is shown on the right. The electrode is 7-mm long, with the last 5 mm shown as a right angle to the polypropylene anchor. Note that the barb of the anchor has not deployed (see text for details).*

Stimulating Electrodes and Methods

Test Electrodes and Stimulator. The optimal area of stimulation to implant the intramuscular electrodes in any given muscle was identified with disk and probe electrodes (Figure 1) connected to a pulse stimulator (12-channel Permaloc stimulator, Synapse Biomedical). The disk electrode (Synapse Biomedical) had a diameter of 4 mm and was used to identify the optimal area to implant the intramuscular electrodes in the diaphragm and abdominal muscles. The probe electrode (disposable monopolar needle electrode, TECA, VIASYS Inc, Madison, WI) had enamel insulation except for the last 5 mm that had been scraped off, and this electrode was used in intercostal and abdominal muscles.

Electrical stimulations were delivered with a 12-channel stimulator. Stimulations consisted of constant-current, balanced, monophasic pulses. The stimulator allowed the operator to control the frequency of stimulation (hertz [Hz]), pulse duration, current amplitude (milliamperes [mA]) (maximal current 25 mA), respiration rate, and combinations of muscles stimulated.

Permaloc Electrodes. After identification of the areas of optimal stimulation (see below), 4 Permaloc electrodes delivering current with negative polarity (Figure 1) were implanted in each of the 3 muscle groups. The electrode consisted of a small helical stainless-steel wire, 30 cm in length. The stainless-steel wire was coated with Teflon (20). The Teflon coating was removed from the distal 7 mm of the electrode. The self-securing polypropylene anchor was made with multiple stands of polypropylene. This anchor was mounted and secured near the stimulating end of the electrode. When the electrode-anchor unit is inserted into a muscle, the anchor expands like an umbrella and secures the electrode in the muscle. Prior to insertion, only the electrode is extending out of the 16-gauge needle. Intramuscular electrodes are inserted into the muscle of interest with a 16-gauge needle (Synapse Biomedical Inc) while maintaining a narrow angle to the muscle. With this maneuver the electrode is implanted to a depth of approximately 5 mm into the muscle (3,4). Permaloc electrodes were also implanted as the positive electrode (ie, return electrode) in target muscles in the last 4 animals (see below).

Positive Electrodes, 6-cm Long and Permaloc. During the initial testing to identify areas of optimal stimulation with disk and probe electrodes, a 6-cm-long positive wire electrode was placed under the skin at midsternum, a location without muscle response. This electrode was removed after the initial testing. At the end of the study, for respiratory pacing in the first 2 animals the positive electrode was a 6-cm-long exposed-wire (Synapse Biomedical Inc) implanted under the skin overlying the spinal processes of the vertebral bodies. For this pacing, in the last 4 animals, the positive electrode (ie, Permaloc electrode) was implanted in the muscle being tested, intercostal or abdominal (see below). This was done to reduce contraction of muscles overlying the spine and to increase the contraction of the target muscles.

Placement of Diaphragm Electrodes

After an abdominal midline incision, the abdominal surface of each hemidiaphragm was identified. The disk test electrode (Figure 1) was used to locate the phrenic motor point in the muscle. Stimulating parameters included 5-mA amplitude, 50-microsecond (μs) pulse duration, 20-Hz frequency, and a stimulus train (0.5 s on alternating with 2.5 s off). Mechanical ventilation did not interfere with the identification of the motor points. Tested first was the area lateral to the vena cava and central tendon, an area of phrenic innervation on the dorsal side of the muscle. The phrenic motor point was identified as the area where the test stimulation elicited the most vigorous diaphragmatic contraction on palpation and visual inspection (3). This was also the area inserted with the first set of intramuscular electrodes (one for each hemidiaphragm). Thereafter, to ensure muscle recruitment as complete as possible, the disk electrode was moved to a location dorsal from the first pair of electrodes (3,4). When again the most vigorous diaphragmatic contraction was identified, a second set of electrodes (one in each hemidiaphragm) was implanted (20). (Of note, only the single bilateral pair of electrodes lateral to the vena cava was used in further respiratory pacing studies, because they were sufficient to produce the target tidal volume of 300 mL; see below).

Placement of Abdominal Wall Electrodes

After placement of the intramuscular electrodes in the diaphragm, we proceeded with the identification of the areas of optimal stimulation of the oblique, transverse, and rectus muscles. Identification of the area of optimal stimulation was carried out first with the disk electrode that was moved along the peritoneal surface of the abdomen. Stimulations of 100-μs, 15-mA pulses delivered at 20-Hz frequency (0.5 s on, 2.5 s off) were used. During this procedure, we determined (on visual inspection and by palpation) that the oblique muscle was best recruited when the disk electrode was placed in an area dorsolateral to the lower margin of the 13th rib. The rectus muscles were best recruited when the disk electrode was moved to the area ventrolateral to the lower margin of the 13th rib. The transverse muscle was recruited when the disk electrode was in the dorsolateral and ventrolateral areas (Figure 2).

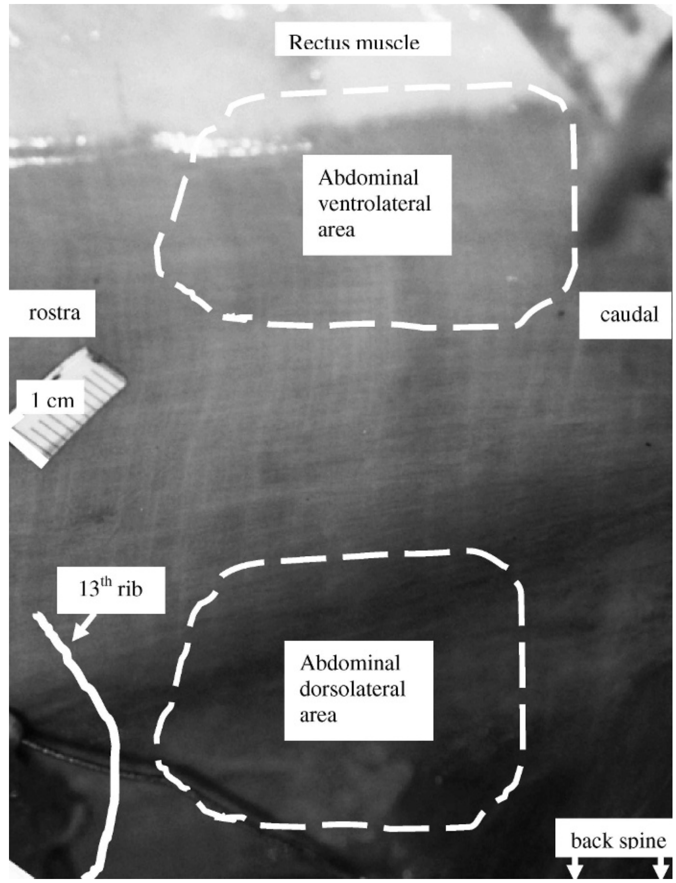

Figure 2. *Photograph of the peritoneal aspect of the left abdominal wall in a representative animal. The ventrolateral and dorsolateral areas (circumscribed by the dashed lines) were identified for optimal stimulation of rectus and oblique abdominal muscles. The transverse muscles were recruited from both areas. The ventrolateral area is near the rectus abdominis muscles and the dorsolateral area is caudal to the 13th rib. Positive electrode not shown in autopsy (see text for details).*

In the last 4 animals, 3 additional protocols were conducted with probe electrodes to further evaluate optimal stimulation locations. This testing was conducted in the dorsolateral area because the strongest abdominal contractions occurred there. First, we placed the probe on the peritoneal surface of the abdominal muscles and observed that the probe produced the same contractions as the disk electrodes. Then, the probe electrode was introduced 5 mm, 15 mm, and just under the skin. The contractile response with the probe at the 5-mm depth was similar to the response produced when the probe had been placed on the peritoneal surface. The contractile response with the probe inserted to 15 mm was analogous to the response at 5 mm in 2 dogs; it was stronger in the third dog and weaker in the fourth dog. In addition, when the probe was advanced to lie just under the skin, muscle activation decreased in all 4 animals.

The second test was designed to compare the contractile response of the abdominal muscles (oblique and transverse) using a 5-mm probe to a probe with 25 mm of exposed electrode. In all 4 animals, the contractile response was more vigorous with the 5-mm electrode than with the 25-mm electrode.

In the third test, we investigated electrode polarity. One 5-mm probe electrode was introduced in the right dorsolateral area and one was in the left dorsolateral area. Stimulation was conducted between the 2 electrodes followed by switching the polarity. In all instances, the positive electrode elicited muscle contractions that were only slightly less intense than those elicited by the negative electrode.

After the identification of the 4 motor points (2 in each side), 4 intramuscular electrodes were implanted bilaterally at a depth of 5 mm from the peritoneal surface. In the first 2 animals, the positive 6-cm electrode (ie, return electrode) was implanted subcutaneously at the level of the third thoracic spinous processes. With this position, however, some coactivation of the paraspinal muscles did occur. After making this observation, we tested alternative positions for the positive electrode and, in the last 4 dogs, determined that the best solution for the positive electrode to achieve the strongest possible contraction of the abdominal wall muscles (while minimizing coactivation of paraspinal muscles) was to implant the Permaloc electrode in the abdominal wall on the right side 4 cm caudal to the 2 implanted negative Permaloc electrodes and midway between them (Figure 2).

Electrode Leads and Postsurgical Care

All electrode leads were inserted via trocar under the skin to the upper back and then brought out through the skin with a 14-gauge needle (ie, each lead had a separate exit site). Thereafter, the electrode leads were placed in a connector (Synapse Biomedical Inc) that was kept in a pocket of the animal's jacket (Medical Arts Inc). Surgical incisions were closed in 3 layers (muscle, subcutaneous, cutaneous) with single interrupted sutures for the outer skin layer. Before transferring the dogs to the postoperative recovery room, bupivacaine (0.25%, 2 mg/kg) was injected subcutaneously near the incisions.

Buphenorphine (0.03 mg/kg) analgesia was administered before recovering from anesthesia and at 8-hour intervals for 3 days. Cephalexin (25 mg/kg, orally) was administered during the first 10 postoperative days. After the sterile surgery, animals were kept overnight in a recovery room where vital signs were monitored. They were then kept in individual runs and were fed ad lib.

Placement of Upper Intercostal Permaloc Electrodes

The second survival surgery was performed 14 days after the first one. During the second surgery, a 6-cm incision in the third intercostal space was made bilaterally. Then, the search for the optimal point of upper intercostal muscle stimulation was conducted with a disk electrode (same stimulating parameters as for the abdominal area except for current set at 10 mA). Disk electrodes elicited vigorous contractions of the serratus and latissimus muscles, both of which are more superficial than the intercostal muscles. Therefore, disk electrodes were abandoned and probe electrodes were used instead. The probe electrode was inserted through the outer muscles to lie in proximity to the lower coastal margin, the intercostal nerve, and the pleural membrane (Figure 3). Test stimulations with the probe electrode were delivered in the lateral chest area at the second through fifth intercostal spaces. At the second intercostal space, we observed variable pectorals muscle coactivation. Thus, only in the first 2 animals, Permaloc electrodes were implanted in the second intercostal muscles. At the third, fourth, and fifth interspace locations, probe stimulations elicited vigorous intercostal muscle contractions and chest expansion. These contractions were associated with only mild coactivation of serratus and latissimus muscles.

In addition to testing the second through fifth intercostal muscles, we assessed the response of the third intercostal muscle to stimulation delivered with the probe electrode in 4 additional locations: (a) against the middle superficial surface of the third rib, (b) just below the lower costal margin of the third rib near the pleural membrane and intercostal nerve (the same location as tested in the immediately above study), (c) just below the upper costal margin of the fourth rib and the pleural membrane, and (d) against the middle superficial surface of the fourth rib. The response at all 4 locations was rated as the same: slight/moderate for both the intercostal muscles for chest expansion and coactivation of serratus and latissimus muscles.

Permaloc electrodes were implanted bilaterally at the 2 most effective intercostal locations identified with any of the testing techniques described above (probe electrode). In the first 2 animals, the intramuscular electrodes were implanted in the second and fourth intercostal spaces. In the last 4 animals, intramuscular electrodes were implanted in the third and fourth intercostal spaces. The intramuscular electrodes were inserted at a narrow angle through the muscles overlying the rib (Figure 3). The positive 6-cm electrode (ie, return electrode) for the upper intercostal muscles was implanted subcutaneously at the level of the third thoracic spinous processes in the first 2 animals. In these animals,

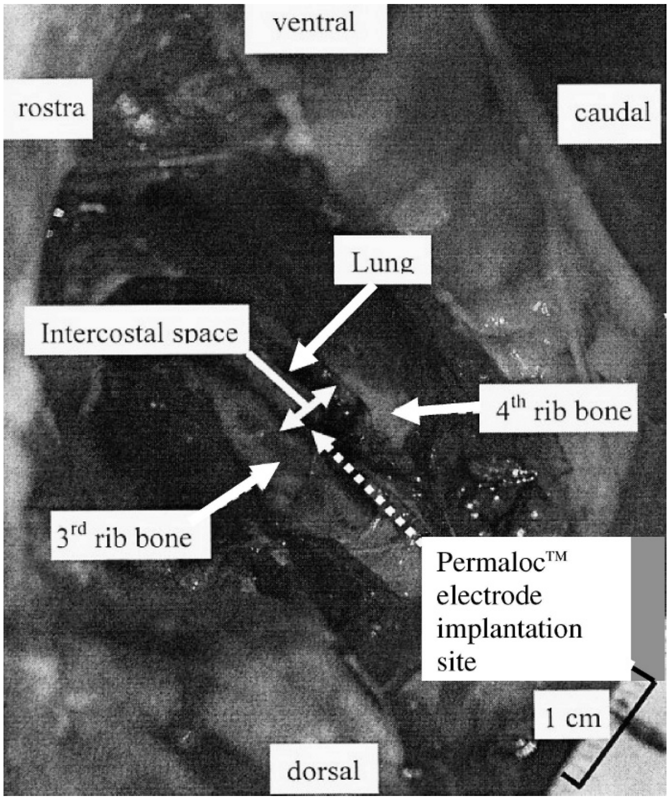

Figure 3. *Photograph of the site of implantation of the intramuscular electrode in the third intercostal muscle in a dog (cadaveric preparation). The muscle layers overriding the third and fourth rib have been dissected and the third intercostal muscles incised to show the underlying lung. The target site for the intramuscular electrode is the area just caudal to inferior costal margin of the third rib and just superficial to the pleural membrane (the intercostal nerve is located medially under the inferior costal margin of the third rib and cannot be seen in this preparation).*

however, we observed coactivation of the paraspinal muscles. To use higher-intensity stimulating current while limiting coactivation of the paraspinal and trapezius muscles, a Permaloc electrode was implanted in the third interspace (ventrolateral area) of the right hemithorax in the last 4 animals. The same steps described at the conclusion of the first surgery (trocar for inserting electrical leads, pain management, and animal housing) were followed after the second survival surgery as well.

Functional Stimulation of Respiratory Muscles

Functional stimulation was carried out at the conclusion of the second surgery in the last 3 animals. The purpose was to assess whether stimulation of the diaphragm in combination with stimulation of intercostal and/or abdominal muscles would augment the tidal volume elicited by diaphragmatic stimulation alone.

During functional stimulation, airflow was monitored with a pneumotachometer (A. Fleish, OEM Medical, Richmond, VA) that had been calibrated with a ball

Table 1. Stimulation Parameters for the Diaphragm, Upper Thorax, and Abdominal Muscles During Functional Stimulation[a]

	No. of Electrodes	Pulse Duration (μs)	Stimulation Period (s)	Current (mA)
Diaphragm	2[b]	50	1.2	Varied[b]
Abdominal	4	100	1	25 mA
Upper thorax	4	100	1.2	Varied[c]

[a] 20 Hz for all 3 respiratory muscles.
[b] Only the single bilateral pair of electrodes lateral to the vena cava was used, because they were sufficient to produce the target tidal volume of 300 mL.
[c] Adjusted to produce a maximal inspiration with not more than slight/moderate unwanted serratus, latissimus, or pectoral muscle contraction.

meter (#13, Cole-Parmer, Vernon Hills, IL). The flow rate signal was also integrated (Gould integrator unit, Gould Inc, Cleveland, OH) to obtain the tidal volume.

Pacing was conducted during hyperventilation-induced apnea. Hyperventilation was achieved by increasing the ventilator rate to approximately 24 respirations per minute until the end-tidal partial pressure of carbon dioxide decreased to 20 to 25 mmHg. Stimulations delivered within 15 seconds of a spontaneous inspiratory effort were excluded from analysis.

Stimulation parameters used in this respiratory pacing are summarized in Table 1. As shown in Figure 4, first, each muscle was stimulated alone. Second, diaphragm stimulation was followed by abdominal stimulation. Third, combined stimulation of the diaphragm and the intercostal muscles was carried out. Last, the combined stimulation of diaphragm and intercostal muscles followed by stimulation of the abdominal muscles was conducted.

Average inhaled and exhaled volumes recorded during functional stimulation are summarized in Table 2. Compared with diaphragm stimulation alone, combined diaphragm plus intercostal stimulation followed by abdominal muscle stimulation increased the exhaled tidal volumes from 312 ± 31 to 486 ± 58 mL ($P = 0.024$).

Pitfalls With Electrode Placement

In approximately 12% of intramuscular electrode insertions into any of the 3 respiratory muscles, the electrode was dragged out of the muscle when withdrawing the 16-gauge needle used for electrode insertion. Dislodging was mainly caused by tissue lodged between the internal wall of the needle and the electrode or between the internal wall of the needle and the polypropylene anchor. To reduce dislodging of the electrode while withdrawing the needle we (a) dipped the needle and intramuscular

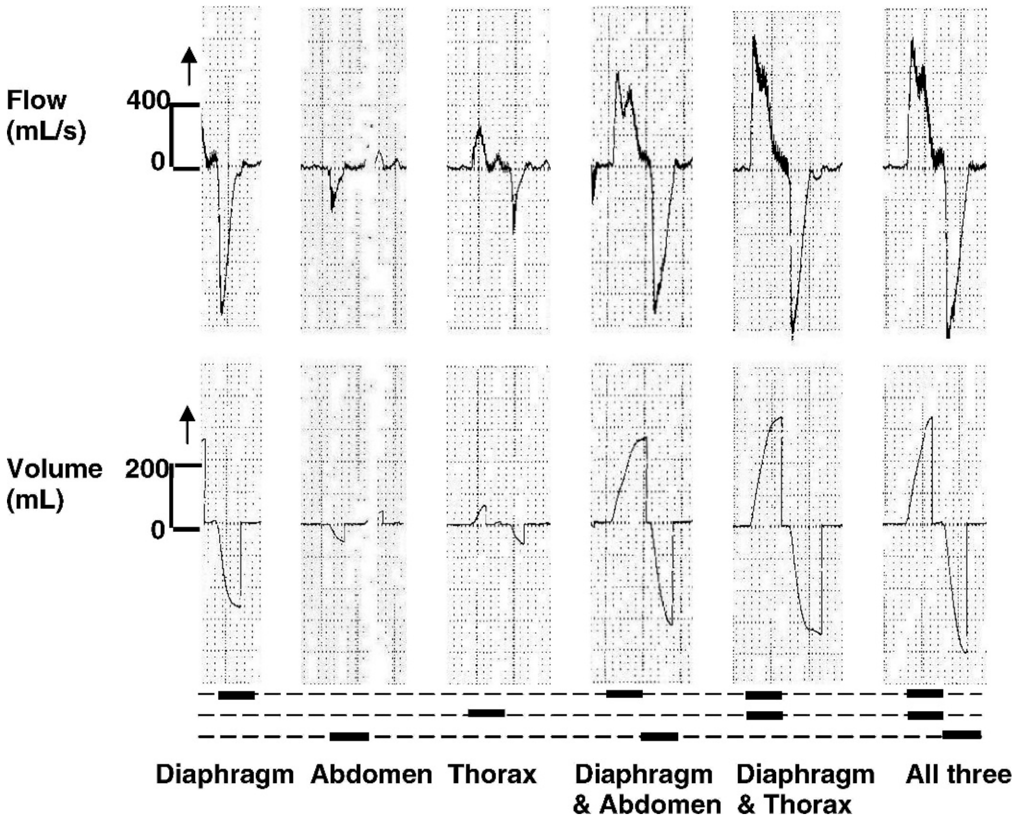

Figure 4. *Tracings of airflow and tidal volume (inhalation positive values) in a representative dog after stimulation of the diaphragm muscle (10 mA), abdominal muscles (25 mA), and upper intercostals (5–10 mA), alone or in combination. Stimulations (dotted line markers: upper for diaphragm; middle for thorax and lower for abdomen) were delivered at 20 Hz with pulse duration of 50 μs (diaphragm) and 100 μs (abdominal and intercostal stimulation). Stimulation trains lasted for 1 or 1.2 seconds. Diaphragm stimulation (Diaphragm) elicited an inspired tidal volume of 260 mL, abdominal stimulation (Abdomen) elicited an exhaled tidal volume of 50 mL, and upper intercostal stimulation current titrated to elicit only slight/moderate contractions of the seratus and latissimus muscles elicited an inspired tidal volume of 60 mL. Combining diaphragm and upper intercostal stimulation followed by abdominal stimulation increased the inspired volume to 340 mL and the expired volume to 400 mL.*

Table 2. Inspired and Expired Volumes Elicited by Stimulation of the Diaphragm, Upper Thorax, and Abdominal Muscles Individually and in Combination

	Inspired Volume (mL)	Expired Volume (mL)
Diaphragm	310 ± 38	312 ± 31
Upper thorax	68 ± 18	
Abdominal		38 ± 20
Diaphragm + upper thorax	417 ± 67	415 ± 77
Diaphragm + abdominal	327 ± 43	387 ± 30
All 3 muscles	438 ± 78	486 ± 58[a]

[a] Significantly different expired volume from diaphragm stimulation alone. $P = 0.024$. Results from 3 animals; standard stimulating parameters for each muscle as described in text.

electrode into normal saline, (b) pulled the 5-mm electrode down onto the needle's lower beveled edge, (c) inserted the needle with the beveled edge facing the tissue while lifting the tissue at the start of the insertion, and (d) inserted the electrode deeper into the muscle (ie, 15 mm instead of 10 mm). Unfortunately, even with these procedures, the electrode occasionally still was dragged out of the muscle when withdrawing the 16-gauge needle used for electrode insertion.

In about 5% of cases, testing of the Permaloc electrode immediately after implantation in any of the 3 muscle groups produced contractions, which we deemed less forceful than the contractions produced with the test electrodes. In these rare instances, the intramuscular electrode was removed, the area of optimal muscle stimulation was reidentified with the test electrodes, and a new intramuscular electrode was implanted. In all instances, the second intramuscular electrode was effective in eliciting the expected muscle contractions.

DISCUSSION

This is the first feasibility study on the use of Permaloc intramuscular electrodes provided with self-securing polypropylene anchors to stimulate abdominal and upper intercostal muscles alone and in combination with diaphragm stimulation. There are 2 novel findings. First, it is possible to develop techniques to implant and stimulate extradiaphragmatic respiratory muscles with intramuscular electrodes. Second, when employing these electrodes, combined stimulation of the diaphragm and intercostal muscles followed by abdominal muscle stimulation increased the exhaled volumes recorded with diaphragm stimulation alone.

Implantation of the Intramuscular Electrodes

Choice of Test Electrodes. The use of test electrodes and a stimulation program of 0.5 seconds on and then 2.5 seconds off allowed for a quick identification of the areas of optimal stimulation of the 3 muscle groups under study. As previously described (8,9), the rating of muscle response elicited by the test electrodes relied on the semiquantitative assessment of the intensity of muscle contraction both by visual inspection and manual palpation. Disk test electrodes performed well for the identification of the areas of optimal stimulation for the diaphragm and abdominal muscles. In contrast, disk electrodes performed poorly when used in the intercostal muscles as a result of coactivation of the latissimus and serratus muscles. This limitation of the disk electrodes was overcome with the use of probe electrodes. Therefore, we recommend the use of disk electrodes for the identification of the areas of optimal stimulation of both diaphragm and abdominal wall muscles and the use of probe electrodes for the identification of the area of optimal stimulation of the intercostal muscles (when used in the abdominal muscles, probe electrodes did not outperform disk electrodes).

Identification of Areas of Optimal Stimulation of the Abdominal Wall Muscles. The muscle groups of interest in the abdominal wall are the rectus abdominis, transverse oblique, and external oblique. With the disk electrodes, we determined that it was impossible to simultaneously stimulate the 3 muscles from a single area of the abdominal wall. Instead, 2 separate areas of optimal stimulation were identified: a dorsolateral area and a ventrolateral area. In the first area, we achieved optimal stimulation of the oblique muscles. In the second, we achieved optimal stimulation of the rectus abdominis muscle. Recruitment of the transverse muscle occurred with both areas of stimulation. In addition, we achieved more vigorous abdominal muscle contraction with avoidance of paraspinal muscles when the return (positive) electrode was implanted in the abdominal wall rather than subcutaneously at the level of the thoracic spinous processes. During bilateral respiratory pacing after surgical closure, strong abdominal muscles were observed at the maximal stimulator output of 25 mA, 100 μs, and 20 Hz. Strong contractions were determined by observing rapid muscle movements, the palpation of firm abdominal muscle contractions, and the upward turning of the pelvis. These results are in agreement with observations for abdominal stimulation (10–14). The dorsolateral area, in particular, is an effective location for abdominal stimulation (11). No adverse effects of abdominal stimulation were observed.

Identification of Areas of Optimal Stimulation of the Intercostal Muscles. The identification of the areas of optimal stimulation for the intercostal muscles was the most technically demanding of all the procedures described in the current investigation. The difficulties encountered in these studies included small anatomic field, care to avoid pneumothorax, and coactivation of other rib cage muscles (latissimus and serratus). After a detailed series of experimental techniques, we determined that the optimal area of stimulation for the intercostals cannot be identified with a single approach in every animal; rather, multiple approaches must be tested. As expected, in all instances, the area of optimal stimulation was located in the medial aspect of the lower costal margin where the intercostal nerve and vascular bundle are located. Of interest, test stimulations delivered when the probe electrode was inserted 5 to 10 mm caudal or rostral to the fourth lower rib margin (third rib), elicited contractions that appeared to be equivalent to those produced when the probe was placed in the medial aspect of the lower costal margin of the third intercostal space. This was probably a result of the monopolar test stimulation, which is known to cause spread of the electrical field (21).

Respiratory Pacing With Intramuscular Electrodes

As previously described (5,6), diaphragm stimulation produced large tidal volumes. Functional stimulation of the upper intercostal muscles elicited only small tidal volumes (Table 2). These contrast with the results of DiMarco et al (5,6). These investigators attributed the large volume responses to spread of the electric field to several thoracic levels from their sites of epidural stimulation along the ventral side of the spinal cord. In other words, DiMarco et al (5,6) probably stimulated the second through the fifth intercostal muscles using the more invasive techniques of stimulation of the ventral aspect of the spinal cord. In contrast, we stimulated only 2 intercostal muscles from each hemithorax.

The exhaled volume with abdominal stimulation will contribute to the tidal volume produced with diaphragm stimulation. When the abdominal stimulation is turned off, greater inflow of air into the lungs occurs. However, the observed exhaled volumes in our current experiments were small, less than 100 mL. These volumes were not larger than our previous report with abdominal stimulation using 4 model microstimulators (9).

DeMarco et al (5) reported strong abdominal muscle contraction with an average exhaled volume of 218 mL produced with epidural electrodes on the dorsal side of the spinal cord in the lower thoracic area. In addition, clinical studies with abdominal surface electrodes and electrodes on the lower ventral side of the spinal cord have produced exhaled volumes greater than 1 L (10–15,18). These large exhaled volumes provide a standard for comparison of alternative techniques. DeMarco et al attributed their large expired volumes during ventral spinal cord stimulation to the spread of the electric field to stimulate the abdominal innervation at several spinal levels (5,6,18). Lin et al also reported that stimulation of more levels with more electrodes is important (19). Several mechanisms probably contributed to our smaller results. Our stimulation was limited to 2 bilateral abdominal sites and to 25 mA. In addition, the location of the positive electrode in the abdominal wall needs to be optimized.

Limitations

Occasionally, the intramuscular electrode was dragged out of the muscle when withdrawing the 16-gauge needle used for the insertion of the intramuscular electrode. This problem was easily overcome by placement of a new electrode. There were unique aspects of testing and implantation of the intramuscular electrode that need further investigation, as described below.

FUTURE DIRECTIONS

This feasibility study supports the possibilities of Permaloc electrodes to be implanted in extradiaphragmatic respiratory muscles and a possible role in respiratory management. The analogous Peterson electrode is already being used widely for respiratory management with diaphragm stimulation in patients with upper cervical level spinal cord injuries (3,4). However, there are limitations of diaphragm pacing for respiratory tidal volumes and cough. Fatigue of the diaphragm can occur during continuous stimulation of the diaphragm alone. The diaphragm by itself may be insufficient during periods of respiratory distress, such as pneumonia and emphysema. The poor respiratory mechanics of inward upper chest movement during diaphragm stimulation limits the efficiency of the diaphragm to produce tidal volumes. There is a particular need for cough involving all respiratory muscles, particularly the abdominal muscles. In the current study, there were limitations of the intramuscular electrode in the upper chest and abdomen; thus, stimulation methods need to be improved.

Five methods should be tried for abdominal stimulation in the future. First, more bilateral stimulating sites would be expected to produce increased abdominal muscle contraction and exhaled volumes. Second, higher stimulating currents should produce stronger muscle contractions. For example, up to 100 mA is used with surface electrodes over abdominal muscles (10–14). Third, our polarity results showed that strong muscle contractions at the positive electrode and the location of the positive electrode in the abdominal wall should be optimized. Fourth, methods to identify effective motor sites with the disk test electrode might be improved by using higher-stimulating currents. Fifth, current implantation sites in the midabdominal muscles may not be optimal, because this location is distal to the origin of lower thoracic nerves that innervate the abdominal muscles. Stimulating along the lower thoracic ribs closer to the spine may increase abdominal muscle responses. However, these locations will require a dorsolateral subcutaneous approach along the lower and dorsal chest wall.

Three methods of upper intercostal nerve stimulation should be tried in the future. First, stimulating intercostal spaces 2 through 5 would be expected to have a positive effect. Probe tests of these 4 interspaces indicated similar chest expansions at each space. Interspaces 6 and 7 should also be evaluated; however, lower interspaces will cause abdominal contraction.

There is clearly a need for a more selective electrode in the upper chest to avoid unwanted muscle contractions. The test with the probe electrode of 4 locations between and on ribs 3 and 4 showed similar responses, indicating spread of the electrical field. However, a limitation of this test was that the electrode at the lower costal margin of the third rib was still probably 2 to 3 mm away from the nerve under the edge of the rib. Thus, an attempt should be made to implant an electrode below the lower costal margin of the rib and closer to the nerve. The intramuscular electrode requiring the large 16-gauge needle for implantation could not be inserted closer to the nerve. Placing bipolar electrodes close together is another method for limiting the spread of the electric field (20). However, more electrodes and leads are required for this stimulation configuration.

CONCLUSIONS

We have developed successful techniques for implanting Permaloc electrodes in the abdominal and upper intercostal muscles. Electrical stimulation delivered via the intramuscular electrodes elicited respiratory muscle contractions. Upper intercostal muscle stimulation was limited by coactivation of serratus and latissimus muscles. Coordinated stimulation of the diaphragm and upper intercostal muscles followed by stimulation of the abdominal wall muscles elicited tidal volumes that were larger than those elicited by diaphragm muscle stimulation alone.

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